

SILICA, CRYSTALLINE (Respirable Size)*

First Listed in the *Sixth Annual Report on Carcinogens* as *Reasonably Anticipated to be a Human Carcinogen* updated to *Known to be a Human Carcinogen* in the *Ninth Report on Carcinogens*

CARCINOGENICITY

Respirable crystalline silica (RCS), primarily quartz dusts occurring in industrial and occupational settings, is *known to be a human carcinogen*, based on sufficient evidence of carcinogenicity from studies in humans indicating a causal relationship between exposure to RCS and increased lung cancer rates in workers exposed to crystalline silica dust (reviewed in IARC, 1997; Brown *et al.*, 1997; Hnizdo *et al.*, 1997).

Crystalline silica is an abundant and commonly found natural material. Hazardous human exposure to RCS, primarily quartz dusts, occurs mainly in industrial and occupational settings. Respirable quartz levels exceeding 0.1 mg/m³ are most frequently found in metal, nonmetal, and coal mines and mills; in granite quarrying and processing; in crushed stone and related industries; in foundries; in the ceramics industry; in construction; and in sandblasting operations.

The link between human lung cancer and exposure to RCS is strongest in studies of quarry and granite workers, and workers involved in ceramic, pottery, refractory brick, and diatomaceous earth industries.. Human cancer risks are associated with exposure to quartz and cristobalite but not to amorphous silica. The overall relative risk is about 1.3 to 1.5. Higher risks are found in groups with greater exposure or longer latency. Silicosis, a marker for exposure to silica dust, is associated with elevated lung cancer rates, with relative risks of 2.0 to 4.0. Elevated risks have been seen in studies that accounted for smoking or asbestos exposure, and confounding is unlikely to explain these results.

Results of animal experiments have shown consistent increases in lung cancers in rats, but not hamsters, chronically exposed to RCS by inhalation. Single intrapleural or intraperitoneal injections of various forms of RCS to rats resulted in lymphomas.

ADDITIONAL INFORMATION RELEVANT TO CARCINOGENESIS OR POSSIBLE MECHANISMS OF CARCINOGENESIS

RCS deposited in the lungs causes epithelial injury and macrophage activation, leading to inflammatory responses and cell proliferation of the epithelial and interstitial cells. In humans, RCS persists in the lungs, culminating in the development of chronic silicosis, emphysema, obstructive airway disease, and lymph node fibrosis. RCS stimulates (1) release of cytokines and growth factors from macrophages and epithelial cells; (2) release of reactive oxygen and nitrogen intermediates; and (3) oxidative stress in lungs. All these pathways contribute to lung disease. Marked and persistent inflammation, specifically inflammatory cell-derived oxidants, may provide a mechanism by which RCS exposure can result in genotoxic effects in the lung

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There is no separate CAS registry number assigned to silica, crystalline (respirable size).

parenchyma. Humans exposed to RCS had increases in sister chromatid exchanges and chromosomal aberrations in peripheral blood lymphocytes. In vitro exposure to some quartz samples induced micronuclei or cell transformation in several cell types, including cells of human origin.

PROPERTIES

Silica is noncombustible, colorless or white, tasteless trigonal "crystals". It occurs naturally in crystalline and amorphous forms and the specific gravity and melting point depend on the crystalline form. The basic structural units of the silica mineral are silicon tetrahedra, SiO_4 . In a tetrahedron, each Si atom is surrounded by four O atoms. Each O atom is shared by two tetrahedra. Slight variations in the orientation of the silicon tetrahedra result in the different polymorphs of silica. Crystalline silica has seven polymorphs. In crystalline silica, silicon and oxygen atoms are arranged in definite regular patterns throughout (Parmeggiani 1983). Quartz, cristobalite, and tridymite are the three most common crystalline forms of free silica. Quartz, cristobalite, and tridymite are interrelated and may change their form under different temperature and pressure conditions. The quartz structure is more compact than that of tridymite or cristobalite (IARC 1987). Quartz melts to glass and has the lowest coefficient of expansion by heat of any known substance. Silica is insoluble in water and most acids but dissolves in hydrofluoric acid forming gaseous silicon tetrafluoride. It is slowly attacked by heating with concentrated phosphoric acid. Crystallized forms of silica are rarely attacked by alkalis (Merck 1989).

USE

Crystalline silica (CS) had many uses because of its unique physical and chemical properties. Commercially produced silica products include quartzite, tripoli, gannister, chert, and novaculite. CS also occurs in nature as agate, amethyst, chalcedony, cristobalite, flint, quartz, tridymite, and in its most common form, sand (IARC 1997). Naturally occurring silica materials are classified by end use or industry. Sand and gravel are produced almost exclusively for road building and concrete construction, depending on particle size and shape, surface texture, and porosity (IARC 1987). High-purity silica sand that may be extracted from sand and gravel operations is also a major industrial commodity. Industrial quartz crystal is another major industrial classification of silica materials (USDOI 1991). Quartz and quartzite products are high-purity products. Silica sand deposits, commonly quartz or derived from quartz, are high in silica content, typically 95%, although impurities may be present up to 25%. Silica sand has been used for many different purposes for many years. In some instances grinding of sand or gravel is required, increasing the levels of dust containing respirable crystalline silica (IARC 1997). Sand with a low iron content and more than 98.5% silica is used in the manufacture of glass and ceramics. Foundry castings is another major use of silica sand; lower purity sand is added to clay to form molds for casting iron, aluminum, and copper alloys. Its use in abrasives, such as sandpaper, grinding and polishing agents, and sandblasting materials, is another significant application. A recent use of silica sand in the United States is in hydraulic fracturing to increase rock permeability to increase oil and gas recovery. Approximately 850,000 tons of silica sand were used for hydraulic fracturing in 1983. Use patterns for silica sand were relatively stable between 1973 and 1983, except for a decreased use for foundry applications. In 1983, glass sand accounted for 37.4% of silica sand use; foundry sand, 26.7%; abrasives, 8%; hydraulic fracturing, 4%; and other uses, 23.9%. Silica sand is also used as raw material for the production of silicon and ferrosilicon metals, abrasive silicon carbide, activated silica, silica gel desiccants, and sodium silicate and as a builder in detergents. It may also be used to filter large

volumes of water, such as municipal water supplies and sewage. Silica bricks and tiles are used to line furnaces and pottery kilns.

Silica sand products are marketed in a wide range of grades, including extremely fine grades known as flours. The principal use for silica sand is in the manufacture of glass (IARC 1997). Silica flour, not always labeled as containing crystalline silica and often mislabeled as amorphous silica, is used industrially as abrasive cleaners and inert fillers (NIOSH 1981). It may be used in toothpaste, scouring powders, metal polishes, paints, rubber, paper, plastics, wood fillers, cements, and road surfacing materials. Silica flour is also used in foundry applications.

Quartz was probably first used as a gem stone several thousand years ago. Its primary use was for jewelry until 1880 when its dielectric and piezoelectric properties were discovered (IARC 1987). Large quantities of pure quartz crystals were required when the applications of pure quartz were discovered for the electronics industries. It was used in radio oscillator circuits to control electromagnetic wave frequencies. Great demands for pure quartz crystals come from the electronics and optical components industries. High-purity synthetic and natural quartz crystals are used for special optical applications such as fiber optics and in the manufacture of watches, microcomputers, television equipment, and wireless communications equipment. Optical grade quartz is used to make lenses and windows in lasers and other devices (IARC 1997).

Cristobalite and tridymite generally occur naturally together (USDOJ 1989). Cristobalite is used in the manufacture of water glass, refractories, abrasives, ceramics, enamels, and in scouring and grinding compounds. Cristobalite is used to decolor and purify oils. Cristobalite and tridymite are formed by heating silica to high temperatures (NIOSH 1986). These products are used in insulation, filters, and furnace linings.

Diatomaceous earth (DE), composed of fossilized diatoms, is used primarily as a substrate for filtration (60% of the world production) because of their intricate microstructure and high ore-to-space volume. DE is amorphous silica, which crystallizes upon calcination. Calcined DE has been used to clarify or filter dry-cleaning solvents, pharmaceuticals, beer, wine, municipal and industrial water, fruit and vegetable juices, oils and other chemical preparations. The next most important use of processed DE (25% of world production) is as fillers. It is used as a filler in paint, paper, and scouring powders. It is also used for their abrasive qualities in polishes to provide flow and color qualities in paints, and to reinforce paper (Kadey 1975; cited by IARC 1987). DE is also used as a carrier for pesticides, fillers in synthetic rubber goods, laboratory absorbents, and in anti-caking agents (IARC 1997).

PRODUCTION

Silica used in commercial products is obtained mainly from natural sources. U.S. production of silica sand has been estimated at 25.8 million tons for 1990 and 27.9 million tons for 1994 (IARC 1997). The United States exports approximately only 4% of its production and for the most part, does not import significant quantities (IARC 1987). Quartz crystals are mined from the minor deposits found in the U.S. Synthetic quartz crystals (hypothermally cultured quartz crystals) are becoming an increasingly important source of quartz production. The U.S. is one of the three major countries (along with Russia and Japan) producing such crystals. The U.S. is also the major producing country of DE, with California being the most important commercial source (IARC 1997).

Most of the high-purity quartz mined in the United States is in the form of lumps, the

precursor material for synthetic quartz crystals (IARC 1987). In the late 1980s, cultured quartz production surpassed natural quartz mining (USDOJ 1990). World dependence on natural quartz crystal is expected to decline because of increased acceptance of cultured quartz crystal as an alternative. The use of lascas to grow synthetic quartz is expected to increase. Estimated U.S. mining production of quartz (lascas) was 600,000 lb in 1989 and 1988, 1.2 million lb in 1986, and 1 million lb in 1985. U.S. production of high-purity quartz in 1983 was 363 tons, 50 tons in 1982, 79 tons in 1981, 182 tons in 1980, and 143 tons in 1979 (IARC 1987). U.S. imports of lascas were estimated to be 200,000 lb in 1989, 215,000 lb in 1988, 146,000 lb in 1987, 52,000 lb in 1986, and 173,000 lb in 1985 (USDOJ 1990).

EXPOSURE

Crystalline silica is the most widely occurring of all minerals, and the most common form of silica is sand (Parmeggiani 1983). It also occurs in nature as agate, amethyst, chalcedony, cristobalite, flint, quartz, and tridymite (Merck 1989). Silica-bearing deposits are found to some degree in every land mass and strata from every period of geologic time. Silica deposits are almost uniformly quartz or derived from quartz. The majority of deposits mined for silica sand consist of free quartz, quartzite, and quartzose deposits such as sandstone (IARC 1987). Quartz constitutes approximately 12% of continental land masses. Granite may contain 25-30% quartz, and shale, up to 30% quartz. Sandstone is predominantly quartz, and limestone may contain substantial amounts of silica. Quartz is the major constituent of commercial sand. Metallic and nonmetallic ore bodies and fossil fuels may contain quartz. Tridymite and cristobalite occur in a number of deposits and can be formed by natural conversion of quartz or amorphous silica (IARC 1987).

Potential occupational exposure to respirable crystalline silica is widespread. Dust containing silica is produced during mining; rock cutting, drilling, crushing, grinding, and milling and screening to refine particle size; abrasives manufacturing; pottery making; and processing of diatomaceous earth. Approximately 3.2 million workers in 238,000 plants in the United States were potentially exposed (IARC 1987). The National Occupational Exposure Survey (1981-1983) estimated that 342,683 total workers, including 37,985 females, were occupationally exposed to quartz and 20,165 total workers, including 1,514 female workers, were exposed to cristobalite (NIOSH 1984). Potential exposures to respirable crystalline silica occur in many occupations and industries: quarrying and mining of coal and other minerals (metals and nonmetals); stone cutting and construction; production of glass and ceramics; foundry work; sandblasting, polishing, and grinding; abrasives manufacture; abrasive blasting; boiler scaling; cement production; plastic manufacturing; refractories; road construction and repair; rubber and paint manufacture; insulation production and installation; quarrying and tunneling; scouring soap production; tile and clay production; and vitreous enameling (NIOSH 1986; IARC 1987).

Potential exposures to respirable crystalline silica occur in nearly all metal and nonmetal mining and milling operations, as well as during mineral processing. More than 45,000 respirable dust samples containing quartz, cristobalite, or tridymite were analyzed for the U.S. Mine Safety and Health Administration between 1971 and 1981 (IARC 1987). Geometric mean respirable silica exposures were below 0.05 mg/m^3 in most of the 15 industry and 14 operation categories included in the survey, but in 64% of the categories, at least 5% of the airborne samples contained more than $0.10 \text{ mg silica/m}^3$. Several mining industries involved respirable silica concentrations of greater than 0.05 mg/m^3 . Of all the samples analyzed, only 175 (<0.4%) were reported to contain cristobalite or tridymite in concentration greater than 1%. Workers in sandstone, clay, and shale and miscellaneous nonmetallic mineral mills had the highest

exposures to silica dust (2.2%-40.9% of the samples exceeded the applicable exposure limit) (IARC 1987). Within the mills the workers with the highest exposures were the baggers, general laborers, and personnel involved in the crushing, grinding, and sizing operations. Cristobalite was found in 168 samples and tridymite, in 3. Personnel grinding and milling quartz or quartzite rock to produce silica flours are also potentially exposed to high levels of silica dust. The particle size of over 98% (by weight) of silica flours is $<5\ \mu\text{m}$. Personal samples of respirable dust were collected at two U.S. silica flour mills. Eighty-five percent of 91 samples from plant employees contained $> 0.05\ \text{mg}/\text{m}^3$ dust made up of 95-98% crystalline silica. Cleaning personnel and bagging machine operators were exposed to average respirable concentrations of 0.65 and $1.0\ \text{mg}/\text{m}^3$, respectively (13 and 20 times greater than the recommended limit). Fifty-four percent of dust samples from 27 U.S. silica flour mills collected between 1974 and 1979 contained more than $0.10\ \text{mg}/\text{m}^3$ respirable silica. In 1984, approximately 2,400 work sites for 15,000-20,000 coal miners exceeded the level of 5% silica. Major sources of silica exposure in these mines were continuous mining operations; roof, floor, and rock band cutting; and roof bolting operations. Floor and roof samples were found to contain 18%-82% quartz, whereas the coal itself contained only 1%-4%. Granite and stone industry and construction personnel are potentially exposed to respirable silica. Sculptors and carvers, stencil cutters, polishers, and sandblasters had the highest potential exposures; the silica content of respirable dust ranged from 4.8-12.2%. In 1972-1982, 29% of 45 samples collected at building construction sites in the United States exceeded the permissible silica exposure limit by a factor of two or more. Findings were similar for construction work other than buildings; potential exposure of twice the silica permissible exposure limit was found in 27% of 270 samples collected in cut stone and stone products industries. Respirable silica exposures in clay pipe factories ranged from $0.01\text{-}0.20\ \text{mg}/\text{m}^3$; 10% of 348 samples collected from glass manufacturing industries had silica concentrations at least two times the permissible exposure standards; 23-26% of samples from clay products and pottery industries had concentrations more than twice the exposure limits; one-third of dust samples from fibrous glass plants had concentrations of respirable silica dust in excess of $0.10\ \text{mg}/\text{m}^3$; levels of respirable crystalline silica in a ceramic electronic equipment parts plant ranged from 0 to $0.18\ \text{mg}/\text{m}^3$; and 23% of samples collected in iron and steel foundries had concentrations in excess of $0.20\ \text{mg}/\text{m}^3$ respirable silica. Respirable silica exposures have been measured for personnel involved with other miscellaneous silica uses and processes. Silica concentrations in the breathing zone averaged $4.8\ \text{mg}/\text{m}^3$ for sandblasters (averages inside and outside protective hoods-not actual worker exposure) and $0.7\ \text{mg}/\text{m}^3$ for helpers. Silica concentrations inside hoods with no air supply ranged from $0.4\text{-}7.7\ \text{mg}/\text{m}^3$. Respirable dust from an abrasive chip factory was found to contain 0.4- 5.8% silica.

NIOSH has compiled a list (with percentage of noncompliance) of industries for which respirable silica samples were found to be at least two times the permissible exposure limit; these include agriculture, 63%; mining, 57%; building construction, 29%; construction other than buildings, 30%; food and food products manufacturing, 52%; textile manufacturing, 27%; paper and paper products, 13%; chemicals and chemical products, 13%; petroleum refining, 11%; glassware and glass products, 11%; structured clay products, 26%; pottery and pottery products, 23%; concrete, gypsum, and plaster products, 12%; cut stone and stone products, 27%; abrasive products, 16%; blast furnace, steel works, and rolling and finishing mills, 32%; iron and steel foundries, 23%; rolling and extruding nonferrous metals, 22%; miscellaneous metal products, 46%; fabricated metal except machinery, 22%; machinery except electrical, 13%; electrical machinery and supplies, 23%; transportation equipment, 20%; and measuring, analyzing, and controlling instruments and photographic and medical instruments, 3.6%; miscellaneous manufacturing, 9%; and all other industries, 15% (IARC 1987).

Nonoccupational exposure to respirable crystalline silica results from natural processes and anthropogenic sources; silica is a common air contaminant. Quartz is the most stable mineral

on the earth's surface and is the most common mineral in waterborne sediments (IARC 1987). Residents near quarries and sand and gravel operations are potentially exposed to respirable crystalline silica. A major source of cristobalite and tridymite in the United States is volcanic rock in California and Colorado (NIOSH 1986). Local conditions, especially in deserts and areas around recent volcanic eruptions and mine dumps, can give rise to silica-containing dust.

Silica and its common forms are found in a large number of consumer products. Talc is derived from crushed rock; spackling, patching, and taping compounds for dry-wall construction are formulated from a blend of minerals including crystalline silica (IARC 1987). Silica flour is added to toothpaste, scouring powders, wood fillers soaps, paints, and porcelain (NIOSH 1986). Consumers may be exposed to respirable crystalline silica from abrasives, sand paper, detergent, cement, and grouts. Crystalline silica also may be an unintentional contaminant; e.g., diatomaceous earth, used as a filler in reconstituted tobacco sheets, may be converted to cristobalite as it passes through the burning tip of tobacco products (IARC 1987). Cristobalite and tridymite are used in insulation, filters, and furnace linings (NIOSH 1986).

REGULATIONS

Respirable Crystalline Silica is federally regulated by EPA, FDA and OSHA. NIOSH proposed a recommended exposure limit (REL) for all forms of crystalline silica of $50 \mu\text{g}/\text{m}^3$ to protect workers from silicosis as well as potential carcinogenicity. The NIOSH recommendation included that silica, crystalline quartz (respirable) be labeled a potential occupational carcinogen. OSHA has established permissible exposure limits (PEL) for an 8-hr time-weighted average (TWA) for crystalline quartz ($< 0.1 \text{ mg}/\text{m}^3$) and crystalline cristobalite and crystalline tridymite ($< 0.05 \text{ mg}/\text{m}^3$).

OSHA also regulates silica, crystalline (respirable) under the Hazard Communication Standard and as a chemical hazard in laboratories. Regulations are summarized in Volume II, Table A-33.